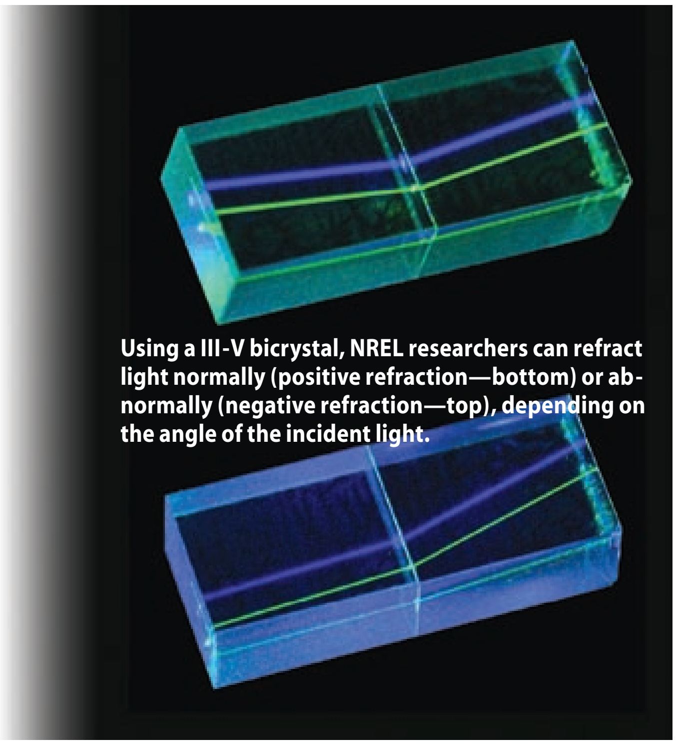
Research Update



Using a III-V bicrystal, NREL researchers can refract light normally (positive refraction—bottom) or abnormally (negative refraction—top), depending on the angle of the incident light.

Negative Refraction of Light

NREL physicists Yong Zhang, Brian Fluegel, and Angelo Mascarenhas have bent light the "wrong way," the first to do so using natural materials. In physics this is a pretty big deal. Why? Consider a stick in water. It appears bent where it enters the water. This is due to the phenomenon known as refraction. When light goes from one medium into another, it changes speed, causing it to alter direction. In refraction, the incident light and the refracted light are always on opposite sides of the normal, a line drawn perpendicular to the interface between the two materials. Thus it has always been.

The ancient dictum that says light must be refracted to the opposite side of the normal was challenged in 1968 by Russian physicist V.G. Vaselago, who suggested that under special circumstances light could be "negatively refracted," or bent to remain on the same side of the normal. In the past couple of years, teams of scientists have begun to show that Vaselago may have been right.

They have designed special, elaborate configurations of "metamaterials" made of copper rings and wires and Teflon, which they have used to negatively refract narrow bands of microwaves. (A metamaterial is an artificially fabricated structure that exhibits properties not found in nature.)

NREL physicists have taken the demonstration a few steps further. Using "real" material —twinned bicrystals of a III-V semiconductor alloy (a twinned bicrystal is one in which two crystals intergrow and are mirror symmetrical about their interface)—they were able to attain negative refraction for visible light. More than that, they showed that, depending on the angle of incidence, they could get positive or negative refraction. What's more, they demonstrated that they could do the same thing for ballistic electrons as well as for light. And, finally, they showed that light could be refracted without losing energy or intensity (due to reflection), which is noteworthy in itself.

Can we harness this new capability? Perhaps. Although this is a new and fundamental discovery, we can already see possible uses in imaging, lens technology, data storage, semiconductor technology, and more. But uses inherent in the ability to steer and bend light, and to collimate electrons, will have to wait on more fundamental research and experimentation.

Enhancing Geothermal Power

Producing power from geothermal energy resources is, in some ways, a remarkably successful endeavor. It is a clean source of power that produces very little carbon dioxide and almost no nitrous oxide or sulfur-bearing gases. Geothermal power plants have high capacity factors and average availabilities of 90% or more. And geothermal power production is a billion-dollar-a-year industry, producing nearly 20% of the nation's non-hydro renewable electric energy. Since 1970, geothermal power plant capacity has grown from 500 MW to more than 2,600 MW today.

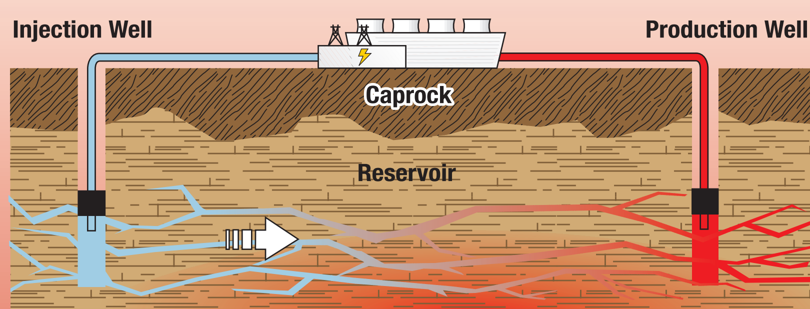
But geothermal power production is currently limited to sites where geothermal energy reservoirs are relatively close to the surface. Because the power plant technology relies on extracting hot water from these reservoirs, they must also consist of fractured rock permeated with water, a geographic coincidence that occurs in limited locations in the West.

Given these limitations, how can the industry grow? The answer is to drill deeper to reach the geothermal heat and, when necessary, to add water and create new fractures. Such "enhanced geothermal systems," or EGS, can potentially expand the use of geothermal energy to any part of the country.

"It becomes almost an unlimited resource," says Gerry Nix, NREL's technology manager for Geothermal Technologies.

The main thrust of EGS is to inject high-pressure water into geothermal hot spots to open fissures that may be blocked with mineral deposits. It's a technique often used today by the oil and gas industry. At the Coso geothermal plant, about 100 miles north of

In EGS, water is injected into a geothermal reservoir to promote fracturing. It is then circulated through the hot rock to heat the water and returned via a production well to produce geothermal electricity.



Los Angeles, a project now under way is fracturing the existing reservoir to increase its size. The effort is expected to boost power production at Coso by 20 MW, to 260 MW total.

EGS also includes efforts to drill deeper at less cost and to convert the hot water into electricity more efficiently. As such, EGS is a graded approach to expanding the geothermal industry. By developing a "toolbox" of new techniques, the industry can gradually increase power production from existing geothermal reservoirs while expanding into areas that are currently beyond its reach. NREL is part of a virtual team spanning the DOE national laboratories that is developing this toolbox.

"NREL is helping to define the next generation of power plants, so we can efficiently convert the heat into power," says Nix. "We have assembled a group of experts to provide the planning, analysis, and integration needed for the scale of this research program."

By successfully developing and employing the EGS toolbox of techniques, DOE expects that the United States could increase its geothermal electric capacity to 20,000 MW by 2020.

Measuring Minority-Carrier Lifetimes

An analysis technique developed at NREL offers a simple, effective way to test the performance of PV materials used to build solar cells. The technique—the Resonant-Coupled Photoconductive Decay System, or RC-PCD—offers a hands-off method to measure the lifetime of so-called "minority carriers" in PV materials.

A solar cell is made from semiconductor layers. One layer is engineered to be n-type, to have an excess of unbonded electrons as potential negative charge carriers. The other layer is prepared as p-type, to have an excess of free "holes" as potential positive charge carriers. Sandwiching the layers together forms a p/n junction with the free electrons and holes traveling across the junction to set up an electric field across the cell.

When light strikes either PV layer, the light energy frees negatively charged electrons within the material, which leaves holes where electrons use to be. Electrons freed by sunlight in p-type material are minority carriers; they tend to be propelled by the electric field across the junction into the n-type material where they migrate toward that end of the cell. Likewise, holes freed by sunlight in n-type material are minority carriers in that material; they are propelled by the electric field across the junction to the p-type material to migrate toward that end of the cell. It is this migration of minority carriers that creates the electric current and power.

Unfortunately, in many parts of a solar cell, the electrical field is too weak to whisk minority carriers off to their designated ends. Instead, the electrons and holes may wander randomly, possibly recombining with each other and wasting their energy as heat instead of producing power. Minority carriers that "live" longer have a greater chance of producing power, so PV materials should ideally have long minority-carrier lifetimes. Defects in the materials create stepping-stones that facilitate recombination, so minority-carrier lifetimes are also an indirect way to measure material defects.

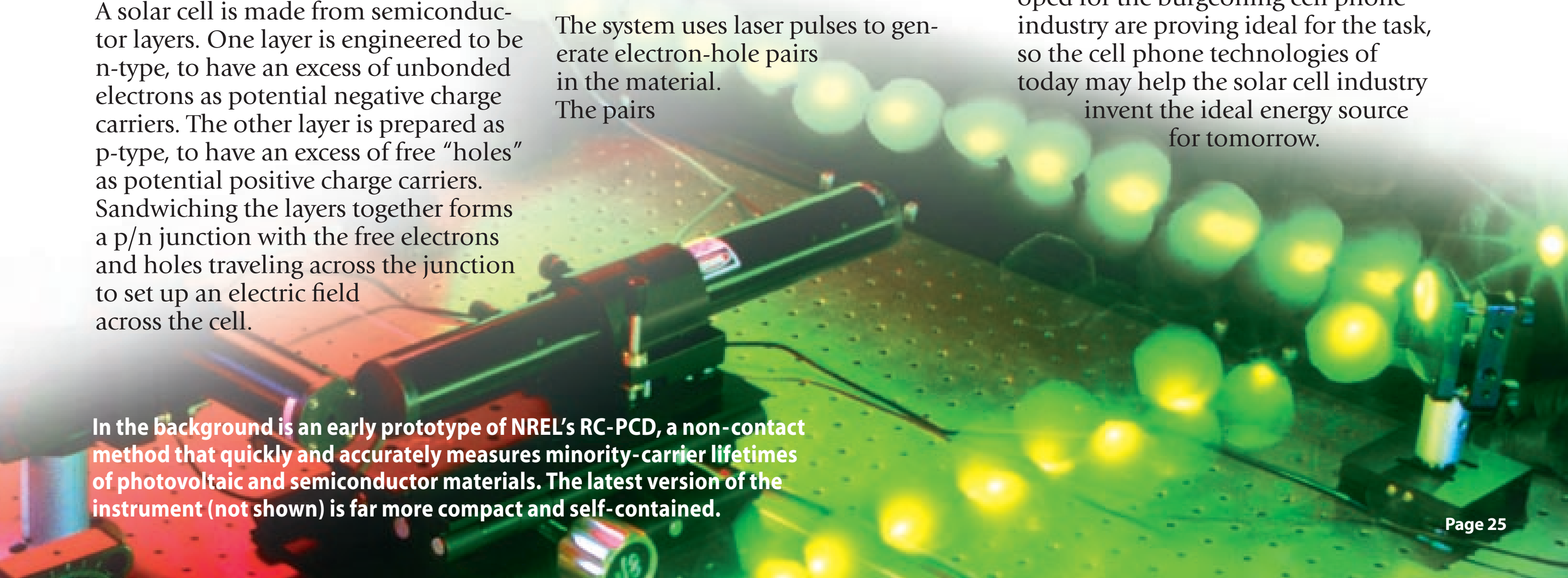
The RC-PCD system, created by an NREL team led by Dick Ahrenkiel, measures minority-carrier lifetimes using a coil of wire. This coil, placed near the material, acts as an antenna, and a high-frequency signal pumped into it generates a low-energy microwave signal. Using electronic circuitry, the antenna can be tuned to perfectly transfer its energy to the material—a technique called resonance coupling.

The system uses laser pulses to generate electron-hole pairs in the material. The pairs change the material's conductivity and cause it to respond differently to the antenna's signal, reflecting part of the signal back to the antenna. Ahrenkiel's team can detect that reflected signal and watch it drop off as the pairs recombine—a process called "photoconductive decay." By pulsing the laser, the system causes the photoconductive decay to occur repetitively. An oscilloscope averages the signals to create a smooth decay curve that provides an accurate measurement of the minority-carrier lifetime.

"We can do things here that nobody else can do," says Ahrenkiel. "It's become a standard in the PV program; we've run hundreds of samples through here. It has a lot of advantages over commercially available systems."

Those systems, mostly invented for the semiconductor industry, operate at higher frequencies that cannot penetrate into the depth of the material as the RC-PCD system can. That's fine for semiconductors, but unsatisfactory for thick solar cells, which depend on the entire thickness of the material to generate a current. The RC-PCD also offers other advantages. It has a greater dynamic range, is far more sensitive and accurate over that range, can measure lifetimes for a wider variety of materials and sample sizes, and has a greater ability to detect defects and their effect on lifetimes.

The system does have a drawback. It is limited to measuring lifetimes of 50 nanoseconds or longer, a limitation that some commercial devices can beat. To overcome that limitation, graduate student Jamiyana Dashdorj is inventing a new, better antenna. Ironically, software and electronics developed for the burgeoning cell phone industry are proving ideal for the task, so the cell phone technologies of today may help the solar cell industry invent the ideal energy source for tomorrow.



In the background is an early prototype of NREL's RC-PCD, a non-contact method that quickly and accurately measures minority-carrier lifetimes of photovoltaic and semiconductor materials. The latest version of the instrument (not shown) is far more compact and self-contained.